

FABRICATION COST OF STEEL AND ALUMINIUM STRUCTURES

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ABSTRACT

The main requirements of modern welded metal structures are the load-carrying capacity (safety), the fitness for production, and economy. These requirements can be met by structural optimization: the economy is achieved by minimizing a cost function. The safety and fitness for production are guaranteed by fulfilling the design and fabrication constraints.

The paper describes the cost calculations, which are founded on material costs and those fabrication costs, which have direct effect on the sizes, dimensions or shape of the structure. Minimum mass and minimum cost structures are usually different.

1 GENERAL

The cost function includes the cost of material, assembly, welding as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. The paper describes the new cost calculations of the different technologies, considering some newer technologies like laser, plasma, waterjet, etc. These costs are the objective functions in structural optimization.

Other costs, like amortization, investment, transportation, maintenance are not considered here. Sometimes we can predict the cost of design and inspection, but usually they are proportional to the weight of the structure. Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the most impact on the structure, if the technology is the same.

1.1 The cost of materials

The cost function of a real structure may include the cost of material, assembly, the different fabrication costs such as welding, surface preparation, painting and cutting, edge grinding, forming the geometry, etc.

$$K_M = k_M \rho V, \quad (1)$$

For steel the specific material cost can be $k_M=1.0-1.3$ \$/kg, for aluminium $k_M= 3.0-3.5$ \$/kg, for stainless steel $k_M= 6.0-7.1$ \$/kg, for glass fibre 20-30 \$/m² depending on the thickness.

K_M [kg] is the fabrication cost, k_M [\$/kg] is the corresponding material cost factor, V [mm³] is the volume of the structure, ρ is the density of the material. For steel it is 7.85×10^{-6} kg/mm³, for aluminium 2.7×10^{-6} kg/mm³, for stainless steel 7.78×10^{-6} kg/mm³, for glass fibre 2.5×10^{-6} kg/mm³. If several different materials are used, then it is possible to use different material cost factors simultaneously in Eq. (1).

1.2 The fabrication cost

$$K_f = k_f \sum_i T_i, \quad (2)$$

where K_f [\$] is the fabrication cost, k_f [\$/min] is the corresponding fabrication cost factor, T_i [min] are production times. It is assumed that the value of k_f is constant for a given manufacturer. If not, it is possible to apply different fabrication cost factors simultaneously in Eq. (2).

1.2.1 Fabrication times for welding

One of the main times of welded steel and aluminium structures are related to welding as follows: preparation, assembly, tacking, time of welding, changing the electrode, deslagging and chipping.

Calculation of the times of preparation, assembly and tacking

The times of preparation, assembly and tacking can be calculated with an approximation formula as follows

$$T_{w1} = C_1 \Theta_{dw} \sqrt{\kappa \rho V} , \quad (3)$$

where C_1 is a parameter depending on the welding technology (usually equal to 1), Θ_{dw} is a difficulty factor, κ is the number of structural elements to be assembled. The difficulty factor expresses the complexity of the structure and it depends on the kind of structure (planar, spatial), the kind of members (flat, tubular). The range of values proposed is between 1-4 [1].

Calculation of real welding time

Real welding time can be calculated on the following way

$$T_{w2} = \sum_i C_{2i} a_{wi}^2 L_{wi} , \quad (4)$$

where a_{wi} is weld size, L_{wi} is weld length, C_{2i} is constant for different welding technologies. C_2 contains not only the differences between welding technologies but the time differences between positional (vertical, overhead) and normal welding in downhand position as well. The equations for different welding technologies can be found in the [2].

Calculation of additional fabrication actions time

There are some additional fabrication actions to be considered such as changing the electrode, deslagging and chipping. The approximation of this time is as follows

$$T_{w3} = 0.3 \sum C_{2i} a_{wi}^n L_{wi} . \quad (5)$$

Table 1 Welding times T_{w2} (min/mm) in the function of weld size a_w (mm) for longitudinal fillet welds, downhand position

Welding technology	a_w [mm]	$10^3 T_{w2} = 10^3 C_2 a_w^2$	Welding technology	a_w [mm]	$10^3 T_{w2} = 10^3 C_2 a_w^2$
SMAW	0-15	$0.7889 a_w^2$	FCAW	0-15	$0.2302 a_w^2$
SMAW HR	0-15	$0.5390 a_w^2$	FCAW-MC	0-15	$0.4520 a_w^2$
GMAW-C	0-15	$0.3394 a_w^2$	SSFCAW (ISW)	0-15	$0.2090 a_w^2$
GMAW-M	0-15	$0.3258 a_w^2$	SAW	0-15	$0.2349 a_w^2$

In is proportional to T_{w2} . It is the 30% of it. The two time elements are as follows:

$$T_{w2} + T_{w3} = 1.3 \sum C_{2i} a_{wi}^n L_{wi} . \quad (6)$$

The welding time for $\frac{1}{2}$ V, V, K and X weldings are very similar for the different technologies: SMAW = Shielded Metal Arc Welding, SMAW HR = Shielded Metal Arc Welding High Recovery, GMAW-CO₂ = Gas Metal Arc Welding with CO₂ , GMAW-Mix = Gas Metal Arc Welding with Mixed Gas, FCAW = Flux Cored Arc Welding, FCAW-MC = Metal Cored Arc Welding, SSFCAW (ISW) = Self Shielded Flux Cored Arc Welding, SAW = Submerged Arc Welding.

1.2.2. Thermal and waterjet cutting

The other main cost is cutting of the elements. The four most commonly used non-contact methods of metal cutting are oxy-fuel gas, plasma, laser, and abrasive waterjet. These four processes are primarily used to make precision external and interior cuts on flat sheet and plate material and tubes.

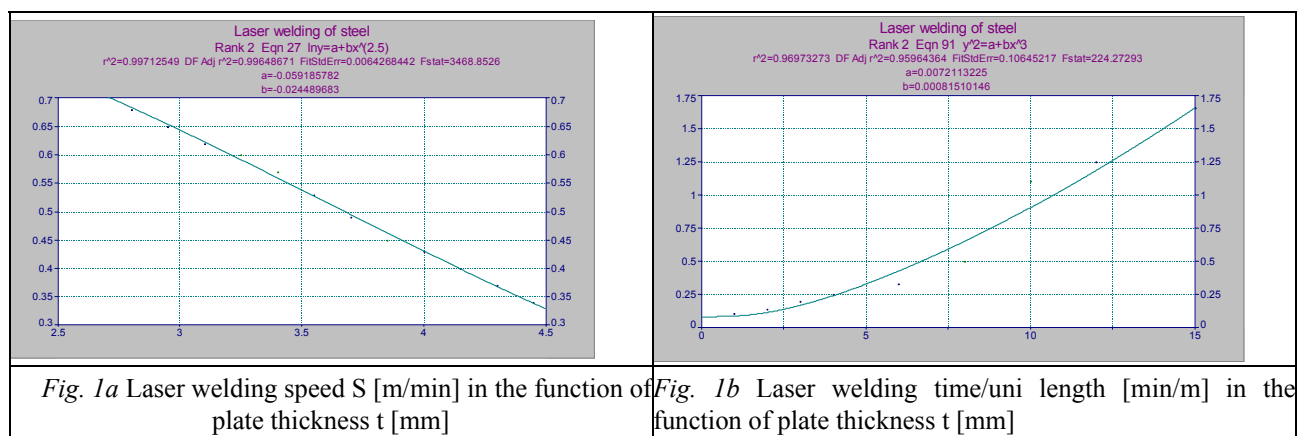
Plate cutting and edge grinding times

Oxy-fuel gas cutting, usually with acetylene gas, was once the only method of thermal cutting. The oxy-fuel torch has a pre-heating flame providing a relatively smooth and regular cut.

Laser welding

The spectrum of laser welding extends from heat conduction welding to deep-penetration welding, a keyhole process in which aspect ratios of up to 10:1 are attained. High power densities permit a concentrated energy input, achieving high welding speeds as well as significantly reduced heat influence and distortion. Compared with arc welding, it allows a much wider range of materials to be welded, and material thicknesses of up to approximately 20 mm can be welded in one pass.

One of the largest advantages that pulsed laser welding offers is the minimal amount of heat that is added during processing. This makes laser welding ideal for thin sections or products that require welding near electronics or glass-to-metal seals. Low heat input, combined with an optical (not electrical) process, also means greater flexibility in tooling design and materials. The speed of laser welding of steel plates can be seen on Fig. 1ab, the value of welding speed [m/min] and time/unit length [min/m] in the function of plate thickness t [mm].



$$S = 1/\ln T = 1/(a + bt^{2.5}) \text{ [mm/min]} \quad (7)$$

$a = -0.05918578241974762$
 $b = -0.02448968345282072$

where S is the welding speed [mm/min], T is time [min], t is thickness [mm].

Thermal and waterjet cutting

The four most commonly used non-contact methods of metal cutting are oxy-fuel gas, plasma, laser, and abrasive waterjet. The first three cutting processes are thermal in nature, while the waterjet method cuts by abrasive erosion. These four processes are primarily used to make precision external and interior cuts on flat sheet and plate material.

Plate cutting and edge grinding times

The cutting and edge grinding can be made by different technologies, like Acetylene, Stabilized gasmix and Propane with normal and high speed.

Table 4 Cutting time of plates, T_{CP} (min/mm) in the function of weld size a_w (mm) for longitudinal fillet welds and T-, V-, 1/2 V butt welds

Cutting technology	Thickness t [mm]	$10^3 T_{CP} = 10^3 C_{CP} t^n$
Acetylene (normal speed)	2-15	$1.1388t^{0.25}$
Acetylene (high speed)	2-15	$0.9561t^{0.25}$
Stabilized gasmix (normal speed)	2-15	$1.1906t^{0.25}$
Stabilized gasmix (high speed)	2-15	$1.0858t^{0.23}$
Propane (normal speed)	2-15	$1.2941t^{0.24}$
Propane (high speed)	2-15	$1.1051t^{0.25}$

The cutting cost function can be formulated using in the function of the thickness (t [mm]) and cutting length (L_c [mm]). Parameters are given in [3]:

$$T_{CP} = \sum_i C_{CPi} t_i^n L_{ci}, \quad (8)$$

where t_i the thickness in [mm], L_{ci} is the cutting length in [mm]. The value of n comes from curve fitting calculations.

The thermal processes and the oxy-fuel gas process in particular share two disadvantages. First, heat changes the structure of metal in a "heat-affected zones" adjacent to the cut. This may degrade some metallurgical qualities at the cut's edge, requiring pre-treatment or trimming. Secondly, tolerances may be less accurate than a machined cut, except for laser cutting.

Laser cutting of steel (Fig. 2) and aluminium (Fig. 3)

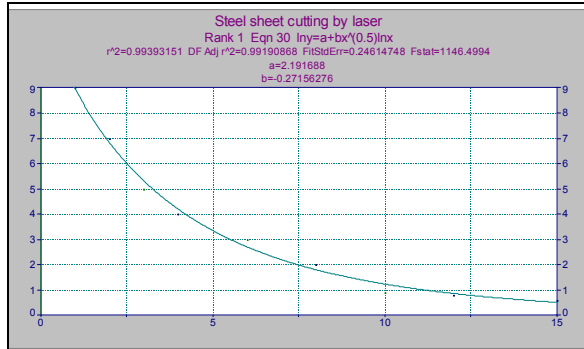


Fig. 2. Steel sheet cutting speed by laser [m/min]

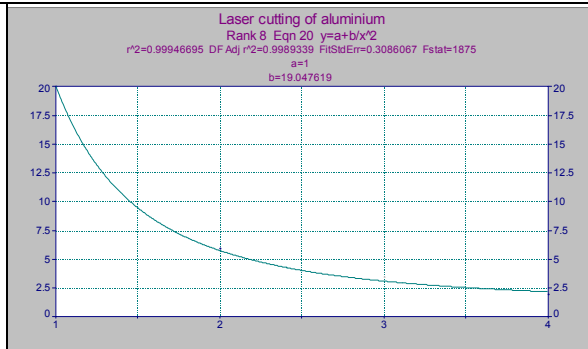


Fig. 3. Aluminium sheet cutting speed by laser [m/min]

Laser cutting allows metals and some non metallic materials to be cut with extreme precision if required. At laser cutting process, a beam of high-density light energy is focused through a tiny hole of the nozzle. When this beam strikes the surface of the work piece, the material of the work piece is cut immediately. Lasers work best on materials such as carbon and stainless steels. Metals such as aluminium and copper alloys are more difficult to cut by laser due to their ability to reflect the laser light as well as absorb and conduct heat.

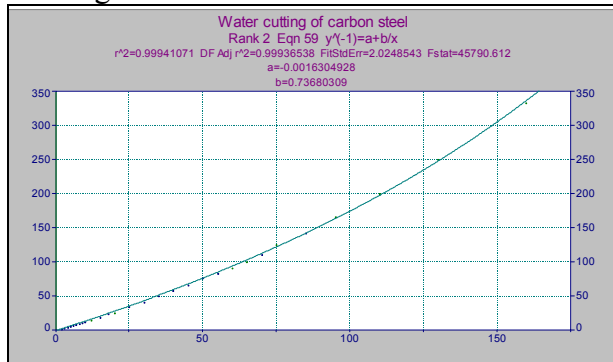


Fig. 5. Waterjet cutting of steel sheet cutting [min/m]

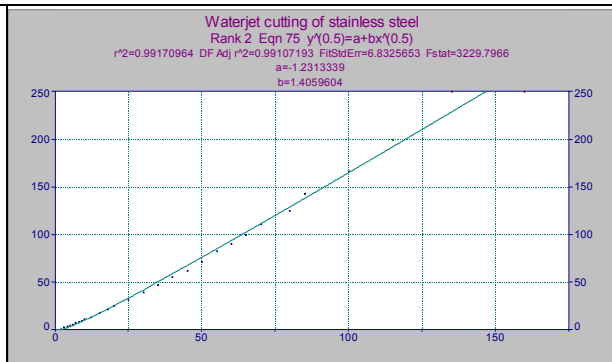


Fig. 6. Waterjet cutting of stainless steel sheet cutting [min/m]

Laser cutting of steel sheets

$$S = 1/\ln T = 1/(a + b t^{0.5}) \text{ [min/mm]}$$

$$a = 2.191688010897978$$

$$b = -0.2715627600304911$$

Laser cutting of aluminium sheets

$$S = 1/T = 1/(a + b/t^2) \text{ [min/mm]}$$

$$a = 1$$

$$b = 19.04761904761905$$

(9)

Waterjet cutting of steel (Fig. 5) and stainless steel (Fig. 6)

A water jet cutter is capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance.

Waterjet cutting, carbon steel 3500 bar

$$S = 1/T = a + b/t \text{ [m/min]}$$

$$a = -0.001630492750216705$$

$$b = 0.7368030917264656$$

Waterjet cutting stainless steel pressure 3500 bar

$$S = 1/T^{0.5} = 1/(a + b t^{0.5}) \text{ [m/min]}$$

$$a = -1.231333913075542$$

$$b = 1.405960445076508$$

(10)

Plasma cutting of steel (Fig. 7) and stainless steel (Fig. 8)

Plasma cutting uses an extremely high temperature, high velocity stream of ionized gas to cut the metal. Plasma temperatures range from about 5500 °C to 28,000 °C. Depending upon the material to be plasma cut, the gases used include: standard compressed shop air, oxygen, argon and hydrogen, or nitrogen and hydrogen. Gas shielding is accomplished with air, water, or carbon dioxide.

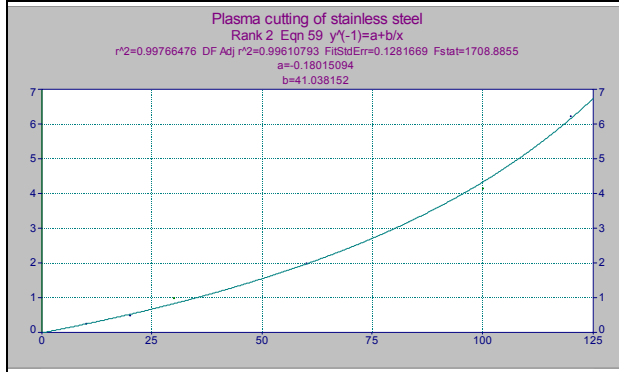


Fig. 7 Plasma cutting of stainless steel [min/m]

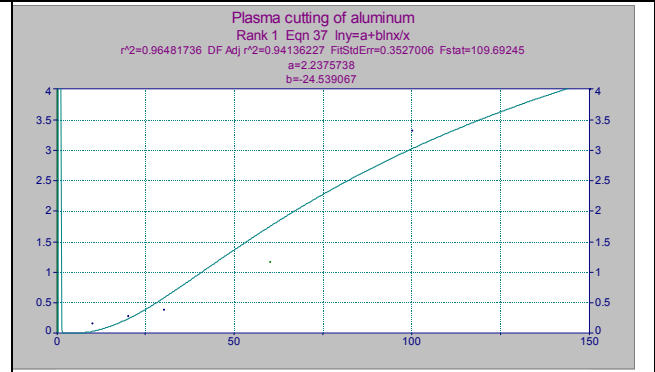


Fig. 8 Plasma cutting of aluminium [min/m]

Plasma cutting requires a torch, a power supply, and an arc-starting circuit. This pilot arc leaves the torch tip as a plasma jet and becomes the path for the main plasma arc. The main arc forms, when the pilot arc contacts the metal's surface. The pilot arc then shuts off, and the cutting torch begins operation.

Plasma cutting of stainless steel

$$S=1/T=a+b/t \text{ [m/min]}$$

$$a= -0.1801509431963638$$

$$b= 41.03815214608195$$

Plasma cutting of aluminium

$$S=1/\ln T=1/(a+b/t^{0.5}) \text{ [m/min]}$$

$$a= 2.97536641707248$$

$$b= -18.8936784318449$$

(11)

1.2.3. Time for flattening plates

$$T_{FP} = \Theta_{df} \left(a_e + b_e t^3 + \frac{1}{a_e t^4} \right) A_p, \quad (12)$$

where $a_e=9.2 \times 10^{-4} \text{ min/mm}^2$, $b_e= 4.15 \times 10^{-7} \text{ min/mm}^5$, Θ_{df} is the difficulty parameter ($\Theta_{df} = 1, 2$ or 3). The difficulty parameter depends on the form of the plate.

1.2.4 Surface preparation time

The surface preparation means the surface cleaning, sand spraying, etc. The surface cleaning time can be defined in the function of the surface area ($A_s \text{ [mm}^2\text{]}$) as follows:

$$T_{SP} = \Theta_{ds} a_{sp} A_s, \quad (13)$$

where $a_{sp} = 3 \times 10^{-6} \text{ min/mm}^2$, Θ_{ds} is a difficulty parameter.

1.2.5 Painting time

The painting means making the ground- and the topcoat. The painting time can be given in the function of the surface area ($A_s \text{ [mm}^2\text{]}$) as follows:

$$T_P = \Theta_{dp} (a_{gc} + a_{tc}) A_s, \quad (14)$$

where $a_{gc} = 3 \times 10^{-6} \text{ min/mm}^2$, $a_{tc} = 4.15 \times 10^{-6} \text{ min/mm}^2$, Θ_{dp} is a difficulty factor, $\Theta_{dp}=1, 2$ or 3 for horizontal, vertical or overhead painting. For complicated structures we use $k_P = 2 \times 14.4 \times 10^{-6} \text{ \$/mm}^2$.

1.2.6. Times of hand cutting and machine grinding of strut ends

At tubular structures a main part of the total cost is the cost of hand cutting and machine grinding of strut ends. We use the following formula [3]:

$$K_{CG}(\$) = \frac{2.5 \pi d_i}{(350 - 2t_i) 0.3 \sin \varphi_i}, \quad (15)$$

where 350 mm/min is the cutting speed, 0.3 is the efficiency factor, d_i and t_i are in mm, : φ_i is the inclination angle of a diagonal brace.

1.2.7. Cost of intumescent painting

Intumescent paintings are getting more and more popular, because they look attractive, does not have a bad effect on slim steel structure view, but the painting is relatively expensive [4]

$$K_{pi} = (k_p + k_{pi}) A_p, \quad (16)$$

where the specific painting cost $k_p = 14 \text{ \$/m}^2$, means the normal painting in two layers (ground and top coat). The additional intumescent painting cost depends on its thickness. The thickness is proportional to the protection time. The cost is $k_{pi} = 20 \text{ \$/m}^2$, for R30, half hour, or $k_{pi} = 60 \text{ \$/m}^2$ for R60, one hour protection. A_p is the full covered surface.

1.3 Total cost function

The total cost function can be formulated by adding the previous cost functions together (depending on the structure some can be zero).

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m} (T_{w1} + T_{w2} + T_{w3} + T_{FP} + T_{SP} + T_P + T_{CG} + \dots) + \frac{K_{pi}}{k_m} + \dots \quad (17)$$

Taking $k_m = 0.5\text{-}1.5 \text{ \$/kg}$, $k_f = 0\text{-}1 \text{ \$/min}$. The k_f/k_m ratio varies between 0 - 2 kg/min. If $k_f/k_m = 0$, then we get the mass minimum. If $k_f/k_m = 2.0$ it means a very high labour cost (Japan, USA), $k_f/k_m = 1.5$ and 1.0 means a West European labour cost, $k_f/k_m = 0.5$ means the labour cost of developing countries. Even if the production rate is similar for these cases, the difference between costs due to the different labour costs is significant.

2 CONCLUSION

In this paper the cost calculation of different welding, cutting, painting, etc. technologies have been described. These cost calculations are founded on material costs and those fabrication costs, which have direct effect on the sizes, dimensions or shape of the structure. The calculated times for different newer technologies like laser, plasma, waterjet, etc. have been included also. These costs are the objective functions in structural optimization. Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the greatest impact on the structure sizes, when the technology is the same.

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